Engineering Evaluation of Full Height (FD) Block Raiser Using Standard Rolled Sections

Victor Guarino – ANL
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1. Introduction

The Block Raiser (BR) is the most expensive and critical piece of installation equipment for the assembly of the NOvA detector. Considerable effort has been devoted to examining several different concepts for constructing this machine. This paper will describe the calculations for a structure constructed using standard rolled sections (W-beams or commonly referred to as I-Beams for non-engineers). The motivation for pursuing commonly available rolled sections is that such a structure would require a minimum of fabrication effort, would be lighter, and the material costs would be less.

It is currently planned to construct blocks of 31 planes on the surface of the BR and then to lift the resulting block into the vertical position. The purpose of this study is to understand the forces acting on the BR, the size of the standard rolled sections that are needed, and to determine a rough idea of the costs to see if the motivation behind this study is correct.

For all of the analysis described the AISC Load Factor Resistance Design (LFRD) will be used. For the initial calculations to determine the size of the beams a beam weight of 62 lbs per foot was assumed and the weight of the beams and block was increased by a factor of 1.4 (dead load) per LFRD specifications. The live load was assumed to be negligible for this exercise.

2. Conceptual Layout of Block Raiser

The conceptual design of the block raiser is shown in Figure 1. The block raiser will consist of an I-beam that is centered on each of the vertical extrusions. The design therefore is modular and can easily be expanded from one to twelve vertical extrusions. These I-beams would be oriented with the vertical extrusions and would be located on the center of each vertical extrusion. These 12 I-beams would then be supported by the much larger W33x118 main support beams. These beams would transfer the entire load outward to the edges of the BR and would be hinged at the front and lifted at the back by the hydraulic cylinder.

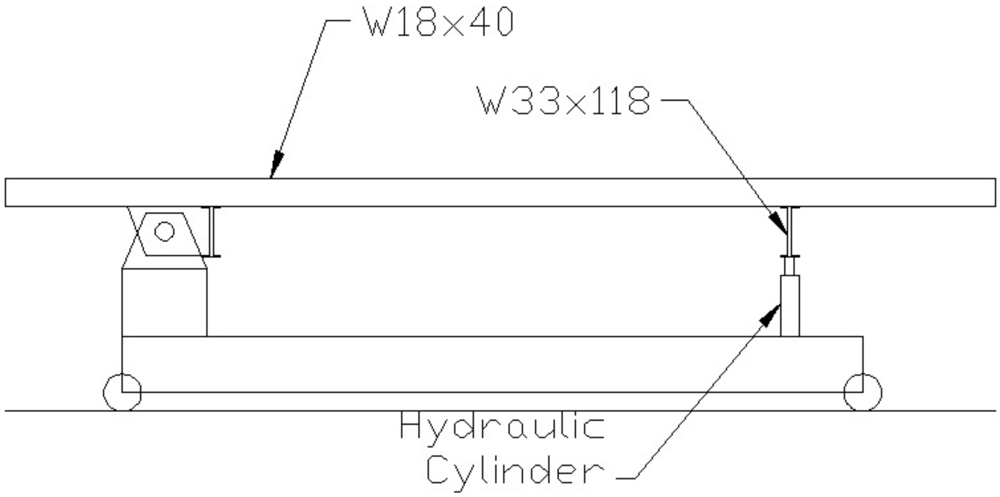

Figure 1 – Schematic of Block Raiser

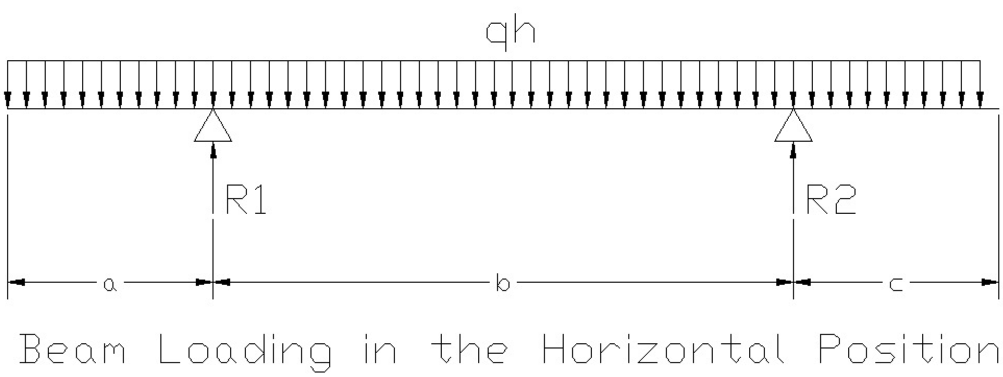

Figure 2 – Schematic of the Rafter Beam Geometry in the Horizontal Position

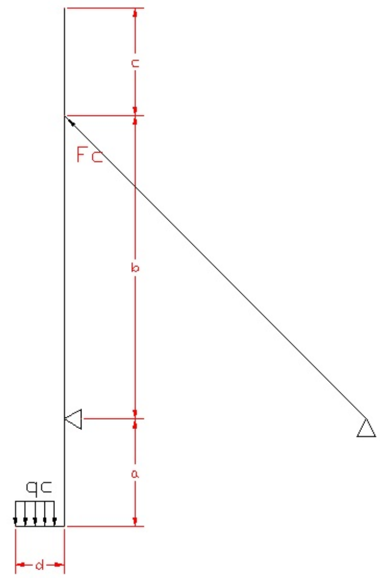

Figure 3 – Schematic Geometry of Block Raiser in the Vertical Position

3. Determination of the Rafter Beam Size

The I-beams aligned with the vertical extrusions are referred to in this study as the rafter support beams because they transfer load to other main support beams similar to the rafters in a building. Figure 2 and 3 show schematically the block raiser in the horizontal and vertical positions respectively and the geometry of the supports that needs to be determined and will be described in the sections below. The main loading on the beam is when the Block Raiser in the horizontal or vertical position and these will be used to bound the loading and deflections for the design.

3.1. Evaluation of Moment in the Horizontal Position of the Block Raiser

Figure 2 shows schematically the I-beam in the horizontal position. The size of the I-beam can be minimized by minimizing the internal moment. It can be shown that the minimum internal moment is achieved by having the moment at the support equal to the moment at the center distance between the supports. This internal moment condition is achieved by having a=c=11ft and b=31ft. Intuitively this condition makes sense by considering the case where a=c=0.0, in this case the moment is maximized at the center distance between supports. As a=c increases from zero to 11ft. the moment at the supports begins to increase while the moment at the center distance between the support begins to decline until equilibrium is achieved at a=c=11ft. Figure 4 below shows the distribution of moments within the beam assuming a 127ton block load distributed over 12 I-beams. The maximum moment is 42.4 kips-ft.

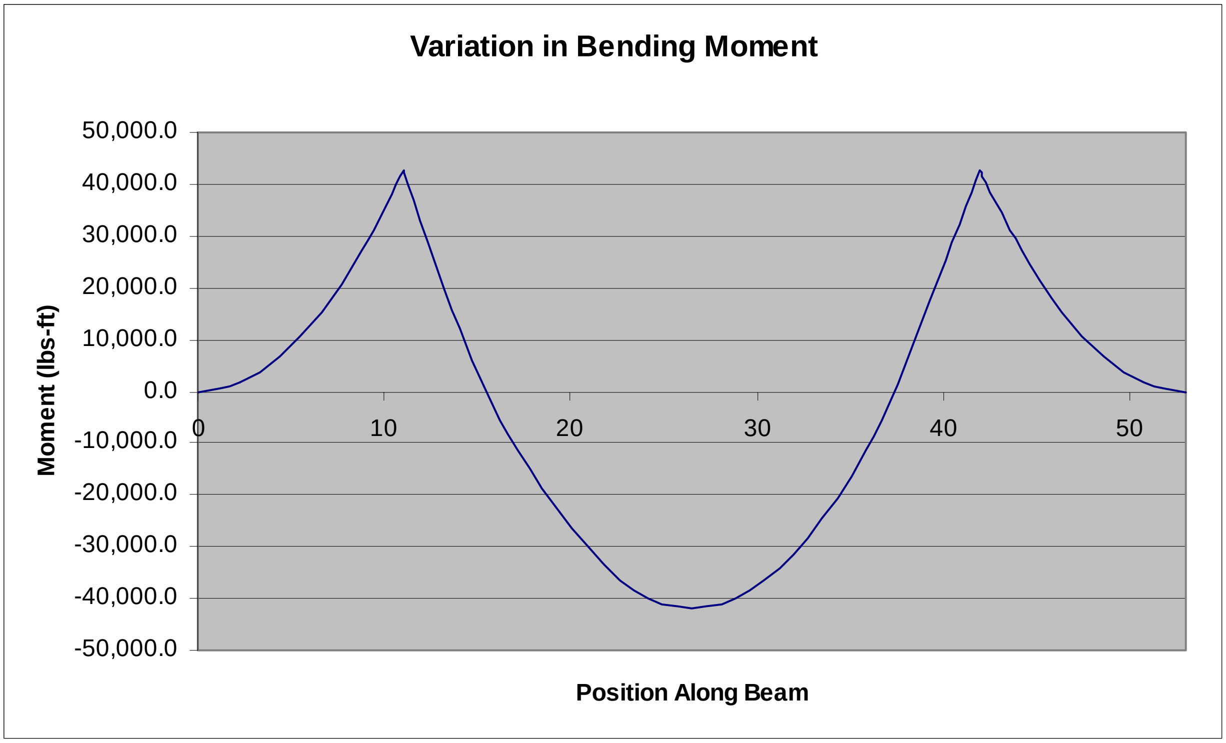

Figure 4 – Distribution of Factored Moment Within BR I-Beam in the Horizontal Position for a=c=11ft and b=31ft

The design of the block raiser with a=c=11ft requires that the block raiser be off the ground by at least 11ft.

3.2. Evaluation of Moment in the Vertical Position of the Block Raiser

The moment in the vertical position is due to the weight of the modules on a fork. It is assumed that each vertical extrusion will be supported by 2 forks. Also, for the design of the forks it is important that the fork be no more than 12” deep because the topping layer of concrete is only 12” thick. It is also assumed that the loading of the modules will be evenly distributed along the length of the fork and that the deflection of the fork will be minimal.

Using 31 planes that are each 66.6mm thick the fork will have to be 80.5 inches long with a distributed load along is of 254 lbs/in. The resulting factored moment is 64.6 kips-ft. A W10x26 I-beam has been chosen for the fork which results in a cantilevered deflection of the I-beam of 0.031 inch.

3.3. Sizing Beam for Moment and Minimum Deflection

A simple calculation (shown in Appendix 1) was done to evaluate the deflection and moment capacity of the beam. A criterion was set that the deflection was limited to a maximum of 0.25 inch. Based on these calculations a W18x40 beam was chosen for the case where a=c=11ft. The moment capacity of the beam is 101.5 kips-ft which is above the applied moment in either the horizontal or vertical positions. The selection of the beam was determined from the deformation criteria.

4. Sizing the Main Support Beam

The rafter beams are supported by the two main beams shown in Figure 1. These beams are used to transfer the loading of the block outward to the edges of the BR. In order to minimize the size of this beam the support points are the same as those determined for the rafters in the sections above. The Main Beams will be supported at a point 11ft from each end of the beam as shown in Figure 1. Each rafter beam applies a load of approximately 18.5kips to the main support beam. With this loading and support locations the maximum bending moment is 372 ft-kips. Using a criteria that the maximum deformation can be no greater than 0.25” a W33x118 beam was selected to meet these requirements. The calculations on this beam are shown in the Appendix.

A simple beam element FEA model was created of the assembled BR table which confirmed the moments and deformations calculated for individual members.

5. Evaluating Requirements for Telescoping Cylinder

A telescoping hydraulic cylinder will be used to lift the block raiser. The length, speed, and force on the cylinder will be described below. It has been assumed that there will be one cylinder for every 2 vertical extrusions. Also, the calculations below assume that a single cylinder will be used to lift the block raiser from the horizontal to the vertical position. However, it is also being considered to have a relatively short standard cylinder with a large capacity to lift the block raiser out of the horizontal position to an angle (30 degrees??) at which time a second telescoping cylinder would take over and complete the lift. This would minimize the length and force capacity of the cylinder.

5.1. Length

The extended length of the cylinder is zero in the horizontal position and increases to a maximum of 43.8ft when the block raiser is in the vertical position.

5.2. Force on Cylinder and Supports

The force on the cylinder is determined by the weight of the block being lifted as well as the cantilever of the block (the distance the CG is above the pivot point. It has been assumed for the calculation of the cylinder force that the each cylinder supports only the weight of a block that is 2 vertical extrusions wide. Also, it has been assumed that the CG of the block/block raiser is located 5.5ft above the pivot point when the block raiser is in the horizontal position.

Figure 6 below shows how the force on the cylinder changes with the angle of the block raiser for the case where a=c=11ft. The maximum compressive force of 17.5 tons occurs in the horizontal position. The force declines to zero when the block raiser is at approximately 71 degrees. As the block raiser continues to lift the CG of the block/block raiser passes the pivot point and the cylinder now acts to restrain the block and the force becomes tensile. A maximum tensile force of 8.8 tons occurs when the block raiser is in the vertical position. There is considerable experience on the Atlas moving system with cylinders making this transition from compression to tension. However, in order to achieve this a double acting cylinder is needed.

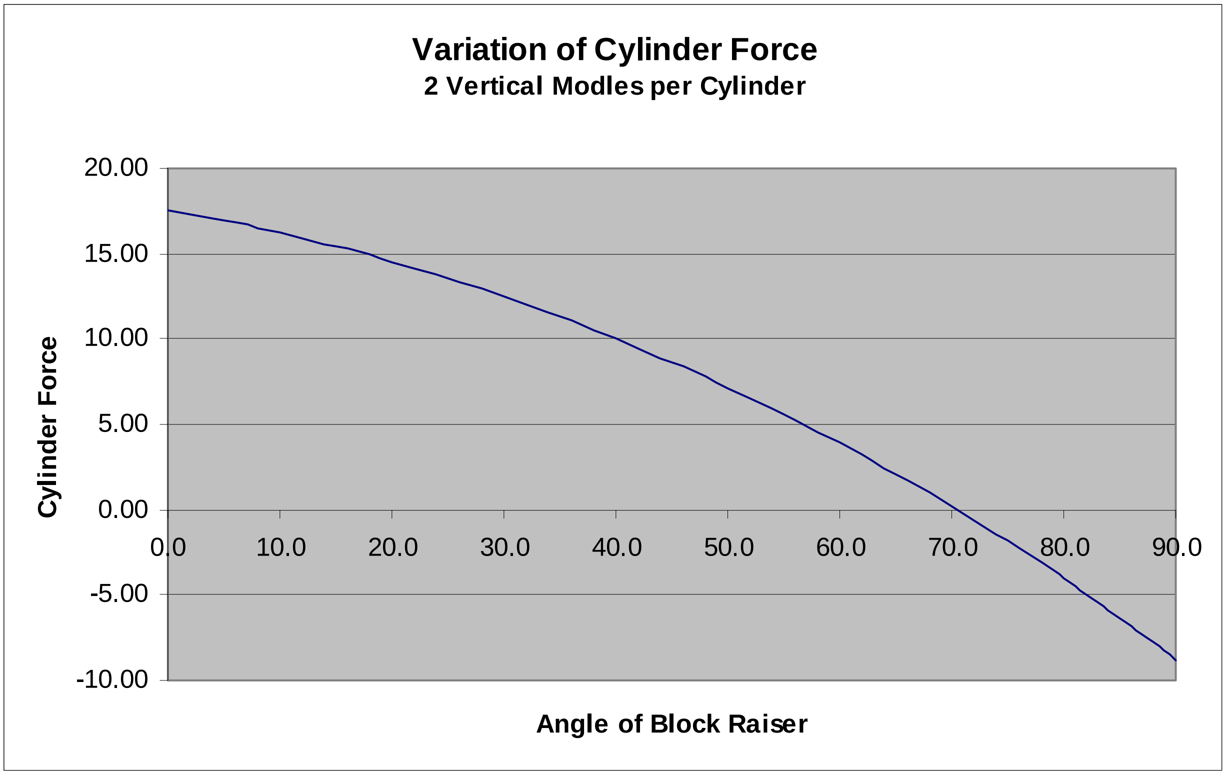

Figure 6 – Variation in Cylinder Force Assuming a 5.5ft CG Offset with a=c=11ft and b=31ft

The change in the cylinder force from compression to tension can be eliminated by the use of a counterbalance. The cylinder force goes into tension because in the vertical position the CG is past the pivot point. A counter balance of equal weight applied on the other side of the pivot points the same distance as the CG would eliminate the moment caused by the off-center CG and keep the cylinder in compression. The problem with the use of a counterbalance is that it increases the weight that has to be lifted and therefore increases the size of the cylinder. Also, the Block Raiser structure becomes more complicated because additional structure/support needs to be added to support the weight of the counter balance. However, readily available double acting telescoping cylinders can eliminate this problem all together and a hydraulic control system can handle the transition from compression to tension.

5.3. Speed

The cylinder speed used in the Atlas moving experience was used as a starting point for examining the speed of the cylinder. For Atlas a 30ton cylinder was safely extended at a velocity of 0.03 ft/sec. Using this cylinder velocity the block raiser angle can be calculated versus time and is shown in Figure 8 below. It takes approximately 25 minutes to rotate the block raiser 90 degrees.

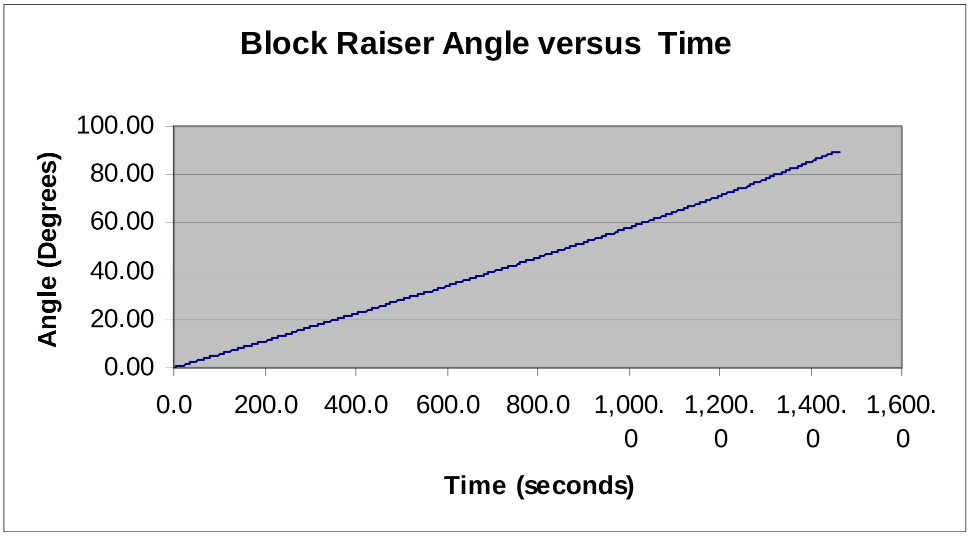

Figure 8 – Angle versus Time for an average cylinder extension velocity of 0.03 ft/sec.

6. Evaluation of Block Tipping

One concern with rotating the block is that as the block approaches 90 degrees and the block raiser comes to a stop that the inertia of the block will cause it to tip forward. In order for the block to tip about the front corner a lateral acceleration of 1.2m/s^2 is needed when the block is in the vertical position. The acceleration of the block cg was calculated using a ramp down acceleration of the cylinder of 0.003ft/sec^2. The tangential and radial accelerations at the CG of the block with respect to the pivot point were calculated. The maximum accelerations were at=0.00048m/sec^2 and ar=0.000006m/sec^2. Since these accelerations are so much smaller than the acceleration needed to tip the block a vacuum system for holding the block against the block raiser is most likely not needed. As a safety precaution though a physical restraint at the top of the block can be added.

7. Evaluation of Block Raiser Tipping in the Vertical Position

When the block is rotated to the vertical position the CG of the block will be in front of the wheels of the block raiser as shown schematically in Figure 9. The block raiser structure will need a counter weight to keep from rotating and tipping around the front wheels. If the counter weight is located above the rear wheels (which is approximately the distance b from the front wheels) then the needed counter weight is equal to the total weight times the ratio of the CG offset divided by the distance “b”. The counter weight therefore will be in the range of 13%-16% of the total weight of the block and block raiser. The weight of the block raiser structure alone might be enough to provide the required counter balance.

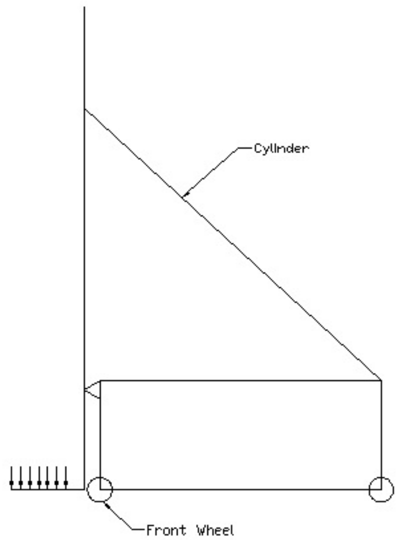

Figure 9 – Schematic Drawing of BR structure

8. Construction Methods

This study has described the use of I-beams for the main support structure. The purpose of examining I-beams is to take a first step in determining the size of the structure that is needed to support the required loads. Budgetary quotes have been obtained for the W33x118 and W18x40 beams of $0.54/lbs. The block raiser table will use 12 W18x40 beams and 2 W33x118 beams for a total weight of approximately 38,000 lbs. for a total material cost of $19k. The cost of fabrication would be minimal and would consist of simply welding/bolting the beams together.

Budgetary quotes have also been obtained for telescoping double acting hydraulic cylinders. A 100ton cylinder that can extend 45ft has been quoted at $25k.

9. Conclusion

This engineering study was a first step in the design of the far detector block raiser. The location of support, forces on cylinders, and size of the structure were all examined. The following conclusions can be made:

- Placing the supports at a=c=11ft creates the smallest bending moment in the structure and allows for the smallest section to be used. The block raiser surface though has to be a minimum of 11ft above the ground.
- The CG of the block is above the pivot point. Therefore, a double acting cylinder is required to control the cylinder as it goes from compression to tension.
- A W33x118 beam can be used to support the rafter beams and allow the block raiser to be supported by only 2 hinges at the front and two hydraulic cylinders.

Gravity Beam Design

RAM SBeam v3.0
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STEEL CODE: AISC LRFD

SPAN INFORMATION (ft): I-End (0.00,0.00) J-End (53.00,0.00)

Beam Size (Optimum)	=	W18X40	Fy	= 50.0 ksi
Total Beam Length (ft)	=	53.00		
Cantilever on left (ft)	=	11.00		
Cantilever on right (ft)	=	11.00		

Mp (kip-ft) = 326.67

LINE LOADS (k/ft):

Load	Dist (ft)	DL	LL
1	0.000	0.040	0.000
	11.000	0.040	0.000
2	0.000	0.440	0.000
	11.000	0.440	0.000
3	11.000	0.040	0.000
	42.000	0.040	0.000
4	11.000	0.440	0.000
	42.000	0.440	0.000
5	42.000	0.040	0.000
	53.000	0.040	0.000
6	42.000	0.440	0.000
	53.000	0.440	0.000

SHEAR (Ultimate): Max Vu (1.4DL) = 10.42 kips 0.90Vn = 152.24 kips

MOMENTS (Ultimate):

Span	Cond	LoadCombo	Mu	@	Lb	Cb	Phi	Phi*Mn
			kip-ft	ft	ft			kip-ft
Left	Max -	1.4DL	-40.7	11.0	0.0	1.00	0.90	294.00
Center	Max +	1.4DL	40.1	26.5	0.0	1.00	0.90	294.00
	Max -	1.4DL	-40.7	42.0	0.0	1.00	0.90	294.00
Right	Max -	1.4DL	-40.7	42.0	0.0	1.00	0.90	294.00
Controlling		1.4DL	-40.7	42.0	---	---	0.90	294.00

REACTIONS (kips):

	Left	**Right**
DL reaction	12.72	12.72
Max +total reaction (factored)	17.81	17.81

DEFLECTIONS:

Left cantilever:

Dead load (in)	=	0.071	L/D	=	3742
Neg Total load (in)	=	0.071	L/D	=	3742

Center span:

Dead load (in)	at	26.50 ft	=	-0.222	L/D	=	1673
Live load (in)	at	26.50 ft	=	0.000			
Net Total load (in)	at	26.50 ft	=	-0.222	L/D	=	1673

Right cantilever:

Dead load (in)	=	0.071	L/D	=	3742
Neg Total load (in)	=	0.071	L/D	=	3742

Gravity Beam Design

RAM SBeam v3.0
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STEEL CODE: AISC LRFD

SPAN INFORMATION (ft): I-End (0.00,0.00) J-End (53.00,0.00)

Beam Size (Optimum)	=	W33X118	Fy	= 50.0 ksi
Total Beam Length (ft)	=	53.00		
Cantilever on left (ft)	=	11.00		
Cantilever on right (ft)	=	11.00		

Mp (kip-ft) = 1729.17

POINT LOADS (kips):

			Flange Bracing	
Dist (ft)	DL	LL	Top	Bottom
2.200	18.60	0.00	No	No
6.600	18.60	0.00	No	No
11.100	18.60	0.00	No	No
15.400	18.60	0.00	No	No
19.800	18.60	0.00	No	No
24.200	18.60	0.00	No	No
28.600	18.60	0.00	No	No
33.000	18.60	0.00	No	No
37.400	18.60	0.00	No	No
41.800	18.60	0.00	No	No
46.200	18.60	0.00	No	No
50.600	18.60	0.00	No	No

LINE LOADS (k/ft):

Load	Dist (ft)	DL	LL
1	0.000	0.118	0.000
	11.000	0.118	0.000
2	11.000	0.118	0.000
	42.000	0.118	0.000
3	42.000	0.118	0.000
	53.000	0.118	0.000

SHEAR (Ultimate): Max Vu (1.4DL) = 107.65 kips 0.90Vn = 488.57 kips

MOMENTS (Ultimate):

Span	Cond	LoadCombo	Mu	@	Lb	Cb	Phi	Phi*Mn
			kip-ft	ft	ft			kip-ft
Left	Max -	1.4DL	-353.7	11.0	0.0	1.00	0.90	1556.25
Center	Max +	1.4DL	372.1	28.6	0.0	1.00	0.90	1556.25
	Max -	1.4DL	-353.7	11.0	0.0	1.00	0.90	1556.25
Right	Max -	1.4DL	-343.3	42.0	0.0	1.00	0.90	1556.25
Controlling		1.4DL	372.1	28.6	---	---	0.90	1556.25

REACTIONS (kips):

	Left	**Right**
DL reaction	115.39	114.07
Max +total reaction (factored)	161.54	159.70

Gravity Beam Design

DEFLECTIONS:

Left cantilever:

Dead load (in)	=	0.082	L/D	=	3234		
Neg Total load (in)	=	0.082	L/D	=	3234		

Center span:

Dead load (in)	at	26.50 ft	=	-0.220	L/D	=	1694
Live load (in)	at	26.50 ft	=	0.000			
Net Total load (in)	at	26.50 ft	=	-0.220	L/D	=	1694

Right cantilever:

Dead load (in)	=	0.090	L/D	=	2947		
Neg Total load (in)	=	0.090	L/D	=	2947		

1. Define Loads

Assume using a W18x40 beam

$kips := 1000lbf$ $ksi := 1000psi$ $plf := \frac{lbf}{ft}$

$W := 127ton + 17.9ton$ Weight of 31 Plane PVC block

$N := 12$ Number of Support Beams

$L := 53ft$ Length of Support Beam

$$w := \frac{W \cdot 2200 \cdot \frac{lbf}{ton}}{N \cdot L}$$ Distributed Block Load (Live Load)

$w = 501.2\,plf$

$DL := 62plf$ Dead Load from Weight of Beam

$Rn := 1.4 \cdot w + 1.4 \cdot DL$ Factored Load

$Rn = 788.5\,plf$

$Mu := 42.4kips \cdot ft$ Factored Moment in the horizontal direction from Spreadsheet calculation

Calculation of moment in the vertical position.

$n := 31$ Number of Planes

$t := 66.6mm$ Thickness of Planes

$Lc := n \cdot t$ Length of cantilevered forks

$Lc = 6.8\,ft$

$Nf := 24$ Number of forks

$$wc := \frac{W \cdot 2200 \frac{lbf}{ton}}{Nf \cdot Lc}$$ Distributed Live Load on Forks

$wc = 1960.9\,plf$

$DL := 26plf$ Dead Load from Weight of Fork -- Assume a W10x26

$Rnc := 1.4 \cdot DL + 1.4 \cdot wc$ Factored Load on Forks

$Rnc = 2781.7\,plf$

$$Muc := \frac{Rnc \cdot Lc^2}{2}$$ Factored moment applied by the forks to the end of the beam.

$Muc = 63.8\,kips \cdot ft$

2.0 Beam Capacity
Assume that Beam is W18x50

Define Strength Reduction Factors

$\phi c := .85$	Strength reduction factor for compression
$\phi v := 0.9$	Strength reduction factor for shear
$\phi := .90$	Strength reduction factor for bending

Define Geometry of Section - W18x50

$h := 16.9\text{in}$	Inside height of beam
$tw := 0.355\text{in}$	Web Thickness
$tf := 0.57\text{in}$	Flange Thickness
$bf := 7.5\text{in}$	Flange Width
$d := 18\text{in}$	Beam Depth
$E := 29000\text{ksi}$	Youngs Modulas of Material
$Fy := 50000\text{psi}$	Yield Strength of Material
$Fu := 65000\text{psi}$	Ultimate Strength of Material
$Ix := 800\text{in}^4$	Moment of Inertia along the strong axis
$Iy := 40.1\text{in}^4$	Moment of Inertia along weak axis
$Ag := 14.7\text{in}^2$	Gross Cross Sectional Area
$Aw := 7.8\text{in}^2$	Area of web used in shear calculations
$cx := 9.0\text{in}$	Half of the depth of the beam perpendicular to the strong axis
$cy := 3.75\text{in}$	Half of the width of the beam perpendicular to the weak axis
$Sx := 88.9\text{in}^3$	Elastic Section Modulas about strong axis
$Sy := 10.7\text{in}^3$	Elastic Section Modulas about weak axis
$rx := 7.38\text{in}$	Radius of gyration about Strong axis
$ry := 1.65\text{in}$	Radius of gyration about weak axis
$Zx := 101\text{in}^3$	Plastic Section Modulas about strong axis

$Zy := 16.6in^3$ Plastic Section modulas about weak axis

$Cw := 3040in^6$ Warping Constant

$J := 1.24in^4$ Torsional Constant

$G := 11200000psi$ Shear Modulas of Material

$Fr := 10000psi$ Residual Stress - 10ksi for rolled shapes and 16.5ksi for welded built-up shapes.

Define Geometric Constraints on Beam/Column

$Lb := 37.5ft$ Unconstrained Length of Beam/Column

$K := 1.0$ End condition for buckling

The values of Cbx and Cby can be calculated by substituting the appriate values in the section below. Cb takes into account the fact that the applied moment is not constant along the entire length of the beam. the buckling formulas are based on the assumption of a constant moment.

Mmax is the absolute value of the maximum moment in the Beam/column
Ma is the absolute value of the moment at the quarter point of the unbraced length
Mb is the absolute value of the moment at the midpoint of the unbraced length
Mc is the absolute value of the moment at the three quarer point of the unbraced length

$Mmax := 46878ft \cdot lbf$

$Ma := 22930ft \cdot lbf$

$Mb := 46200ft \cdot lbf$

$Mc := 22930ft \cdot lbf$

$$Cbx := \frac{12.5 \cdot Mmax}{2.5Mmax + 3 \cdot Ma + 4 \cdot Mb + 3 \cdot Mc}$$

$Cbx = 1.333$

Calculate the Design Strength of the Beam

Bending Design Strength About the Strong (X) Axis

First calculate Lp and Lr

$Lp := 1.76 \cdot ry \cdot \sqrt{\frac{E}{Fy}}$ AISC Eq. F1-4 Lp is the length at which instability begins.

$Lp = 5.8\,ft$

$$X1 := \frac{\pi}{Sx}\cdot\sqrt{\frac{E\cdot G\cdot J\cdot Ag}{2}}$$
AISC Eq. F1-8

$$X2 := \frac{4\cdot Cw}{Iy}\cdot\left(\frac{Sx}{G\cdot J}\right)^2$$
AISC Eq. F1-9

$$Lr := \frac{ry\cdot X1}{(Fy - Fr)}\cdot\sqrt{1 + \sqrt{1 + X2\cdot(Fy - Fr)^2}}$$
AISC Eq. F1-6 Lr is the value of the unbraced length at the boundary between inelastic and elastic LTB.

$Lr = 15.6\,ft$

$Mpx := Fy\cdot Zx$

Plastic Moment which applied when Lb is less than or equal to Lp - AISC Eq. F1-1

$Mpx = 420.8\,kips\cdot ft$

$Mrx := (Fy - Fr)\cdot Sx$

Mr defines the transition from inelastic LTB to elastic LTB when Lb=Lr

$Mrx = 296.3\,kips\cdot ft$

$$Mnax := Cbx\cdot\left[Mpx - (Mpx - Mrx)\cdot\left(\frac{Lb - Lp}{Lr - Lp}\right)\right]$$
Mna is the moment when Lb is between Lp and Lr
AISC Eq. F1-2

$Mnax = 23.0\,kips\cdot ft$

$$Mcrx := Cbx\cdot\frac{\pi}{Lb}\cdot\sqrt{(E\cdot Iy\cdot G\cdot J) + \left[\left(\frac{\pi\cdot E}{Lb}\right)^2\cdot Iy\cdot Cw\right]}$$

Mcr is the moment when Lb is greater than Lr
AISC Eq. F1-12 and F1-13 this expression is applicable to compact doubly symmetric I-shaped members, channel sections loaded in the plane of their webs, and I-shaped singly symetric sections with their compressoin flanges larger than their tension ones. See Sections F1.1.2b and F1.1.2c of the LRFD Specification for Mcr for solid rectangular bars, symmetric box sections, tees, and double angles.

$Mcrx = 112.8\,kips\cdot ft$

$$Mnx := \begin{vmatrix} Mpx \quad \text{if } \; Lb \le Lp \\ (1.5 \cdot Fy \cdot Sx) \quad \text{if } \; Lb \le Lp \wedge Mpx > 1.5 \cdot Fy \cdot Sx \\ Mnax \quad \text{if } \; Lp < Lb \le Lr \\ Mpx \quad \text{if } \; Lp < Lb \le Lr \wedge Mnax > Mpx \\ Mcrx \quad \text{if } \; Lb > Lr \\ Mpx \quad \text{if } \; Lb > Lr \wedge Mcrx > Mpx \end{vmatrix}$$

Mn is the design moment. This expression defines Mn based on Lb as well as defines the upper limit of Mn.

$Mnx = 112.8\, kips \cdot ft$

$\phi Mn := \phi \cdot Mnx$

$\phi Mn = 101.5\, kips \cdot ft$